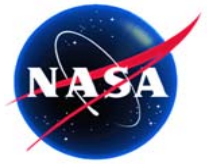

Pressure Profiles in a Loop Heat Pipe under Gravity Influence

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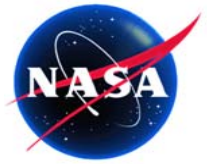
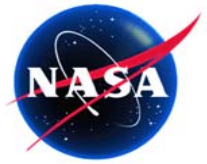


Outline

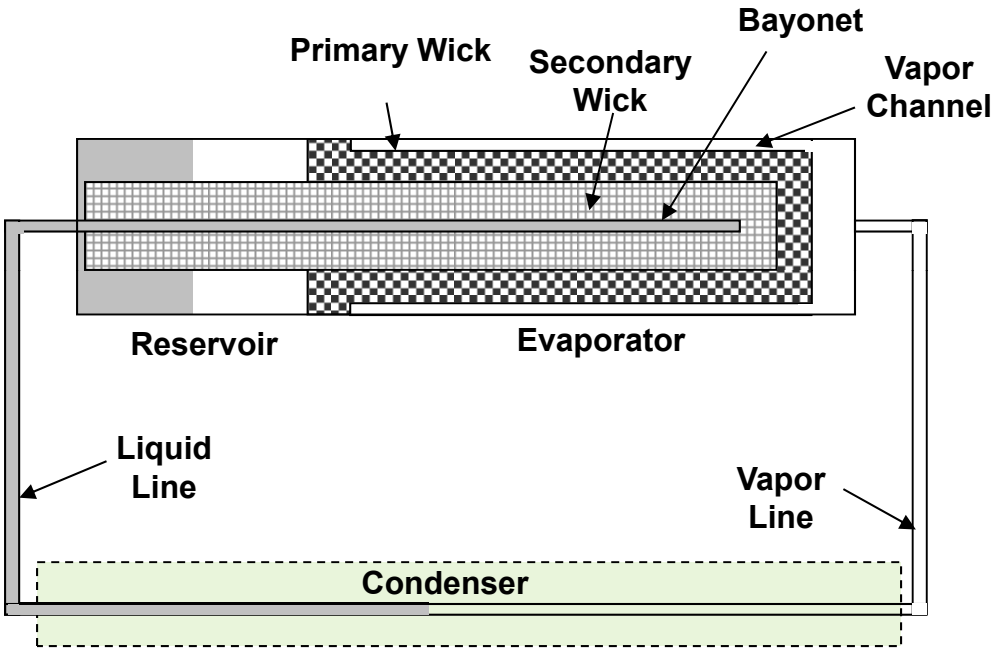
- Introduction
- LHP Operation Under Gravity-Neutral Environment
- LHP Operation Under Anti-Gravity Environment
- LHP Operation with Gravity Assist
- LHP Transient Operation with Reverse Liquid Flow
- LHP Operation with Vertical Condensers
- Summary and Conclusions

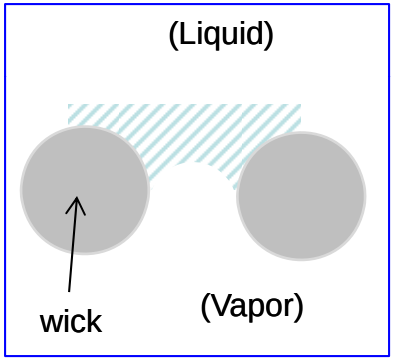


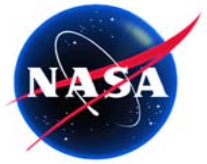
Introduction

- **Most instruments using LHPs require ground tests at instrument and/or spacecraft level testing.**
- **Gravity can have profound effects on LHP operation.**
- **The overall effect on the LHP operation due to gravity depends on many factors.**
  - **Test configuration/orientation**
  - **Elevation of condenser relative to evaporator**
  - **Heat load to evaporator**
  - **Condenser configuration**
  - **Mode of LHP operation**

Flow Schematic of a Loop Heat Pipe





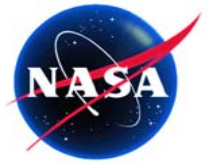


LHP Operation Under Influence of Gravity

- Under gravity neutral and anti-gravity conditions, the fluid circulation in an LHP is driven solely by the capillary force.

- With gravity assist, however, the flow circulation can be driven by the combination of capillary and gravitational forces, or by the gravitational force alone.

- For a gravity-assist LHP with a fixed elevation between the condenser and evaporator, there exists a threshold heat load below which the LHP operation is driven by gravitational force alone and above which the LHP operation is co-driven by capillary and gravitational forces.



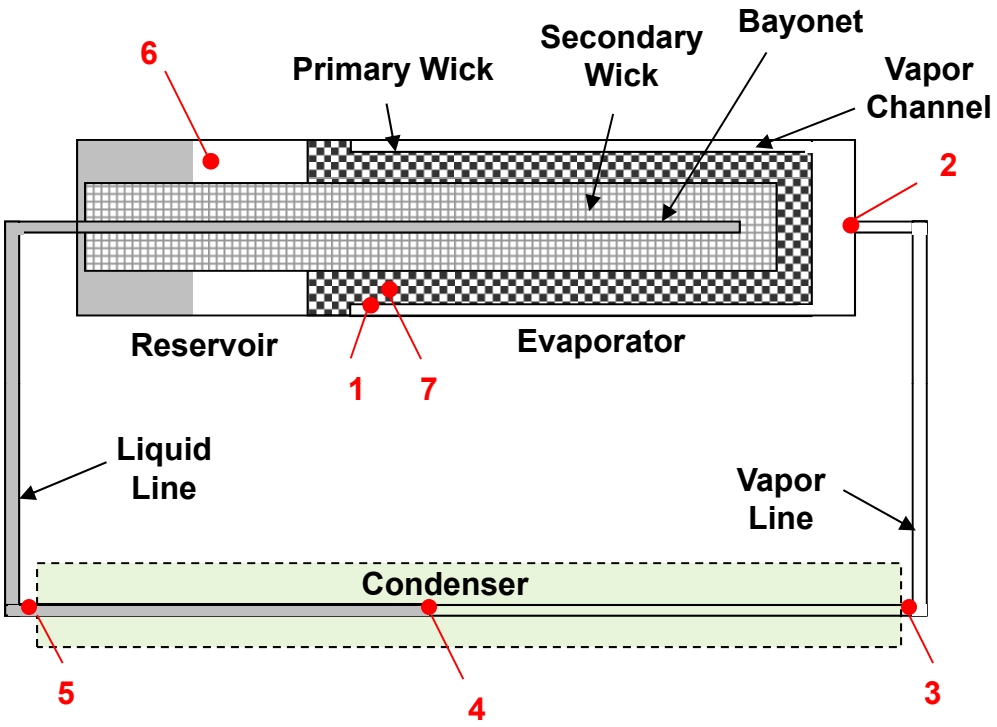
Gravity-Assist LHP Operation

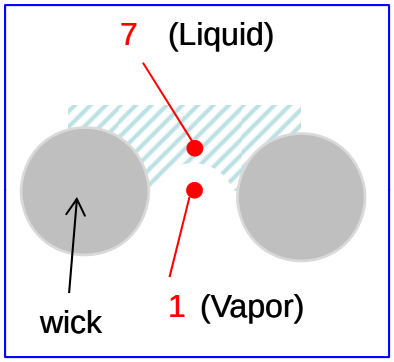
- It has been observed during TV testing that the LHP could display some unexpected behaviors due to gravity assist.

- Such unexpected LHP behaviors due to gravity assist can have significant impacts on flight projects in terms of ground test validation, schedule, and cost.

- A better understanding the gravity effect on LHP operation is needed.

Pressure Drop in Gravity-Neutral LHP Operation Capillary Force Driven



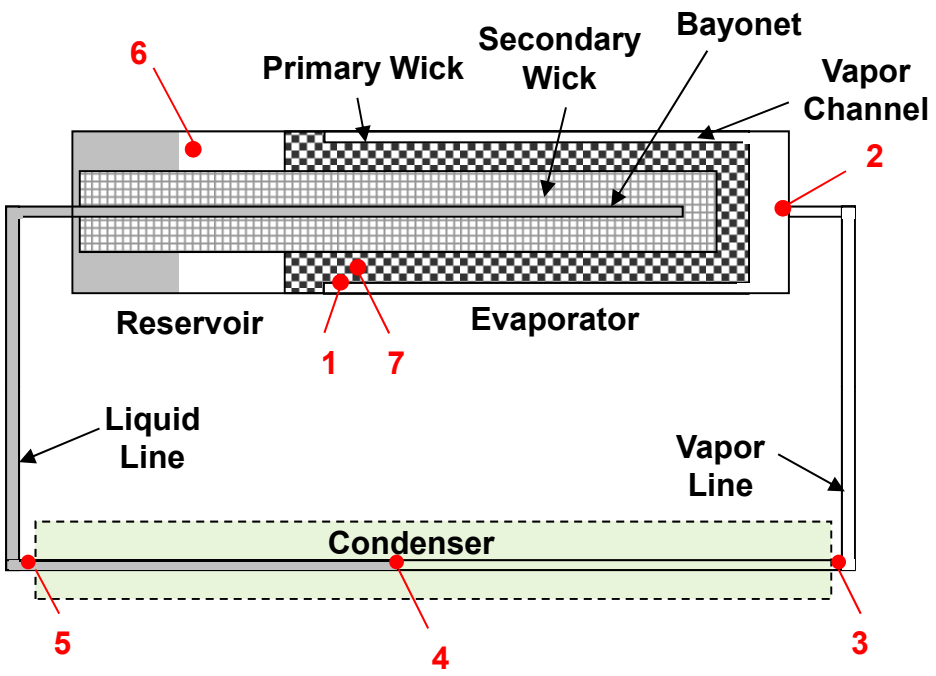


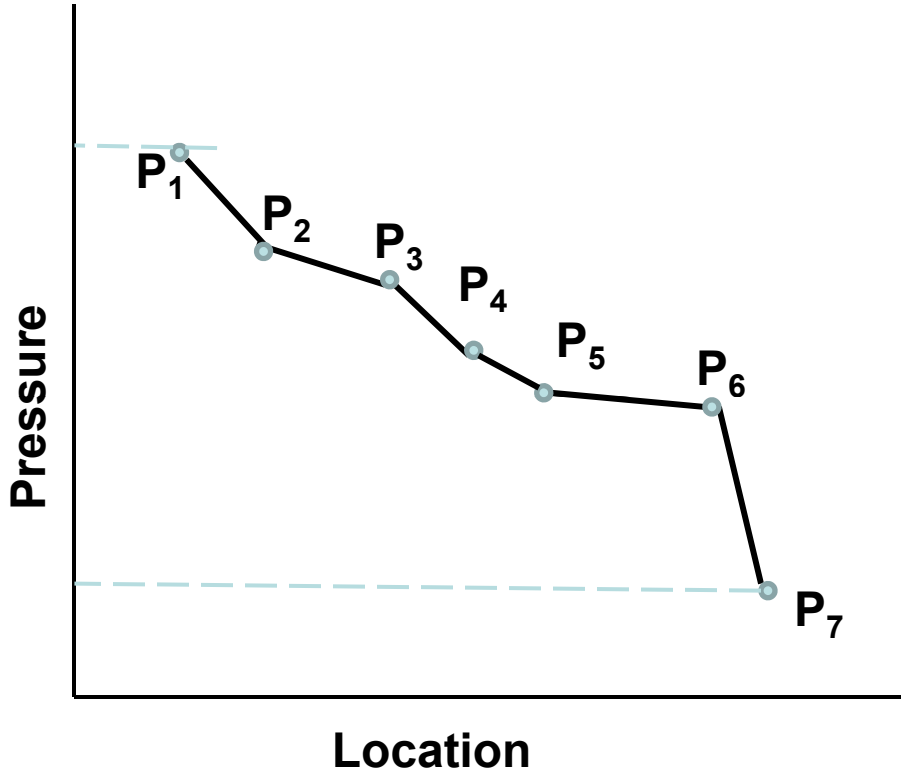
$$\Delta P_{tot} = \Delta P_{groove} + \Delta P_{vl} + \Delta P_{cond} + \Delta P_{ll} + \Delta P_{wick}$$

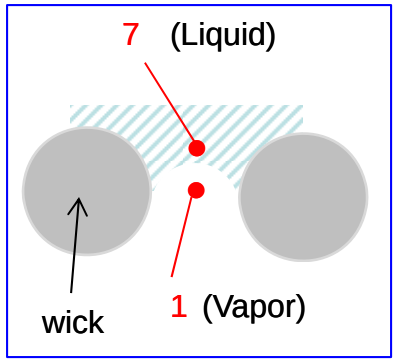
$$\Delta P_{cap,max} = 2\sigma \cos\theta / R$$

$$\Delta P_{tot} \leq \Delta P_{cap,max}$$

Pressure Profile in Gravity-Neutral LHP Operation
Capillary Force Driven

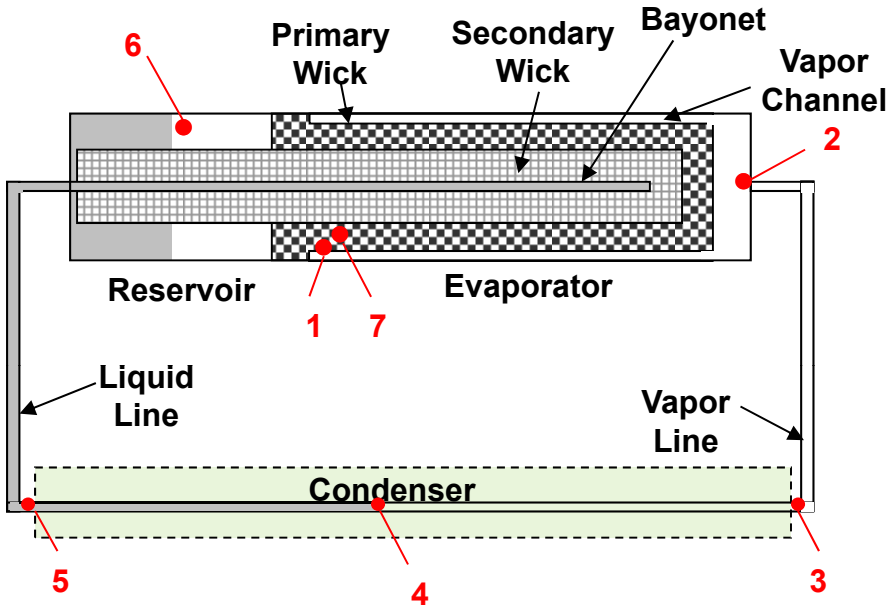


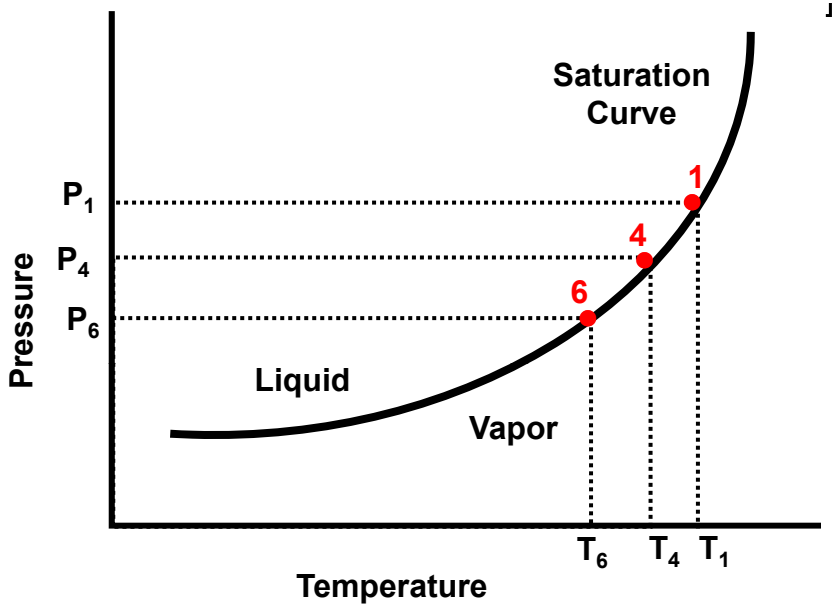




- Evaporator core is considered part of reservoir.
- P_6 is the reservoir saturation pressure.
- All other pressures are governed by P_6
- All pressure drops are viscous pressure drops.

Pressure-Temperature Constraints in LHP Operation



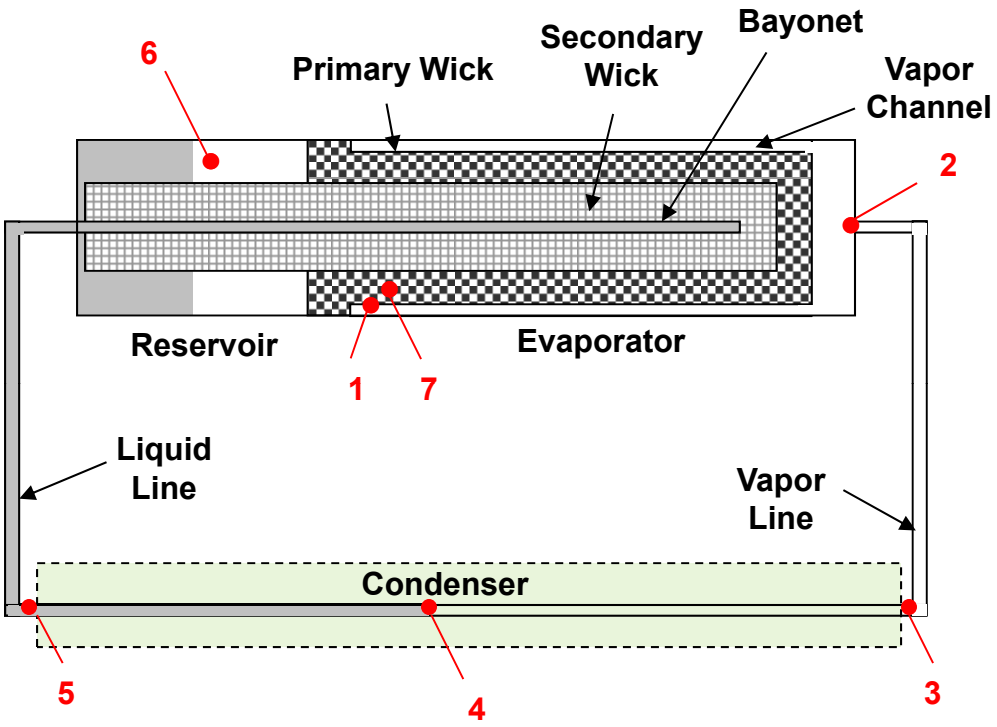


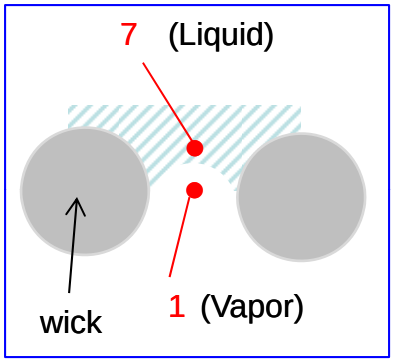
$$P_E - P_{cc} = (dP/dT)\,(T_E - T_{cc})$$

$$P_E - P_{cond} = (dP/dT)\,(T_E - T_{cond})$$

$$P_{cond} - P_{cc} = (dP/dT)\,(T_{cond} - T_{cc})$$

Pressure Drop in Anti-Gravity LHP Operation Capillary Force Driven



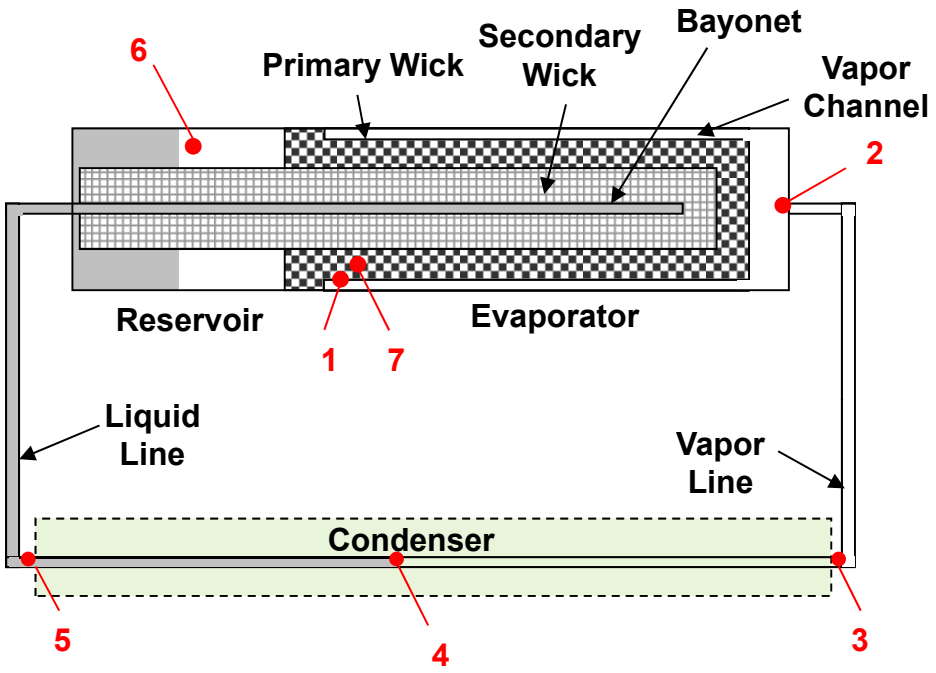


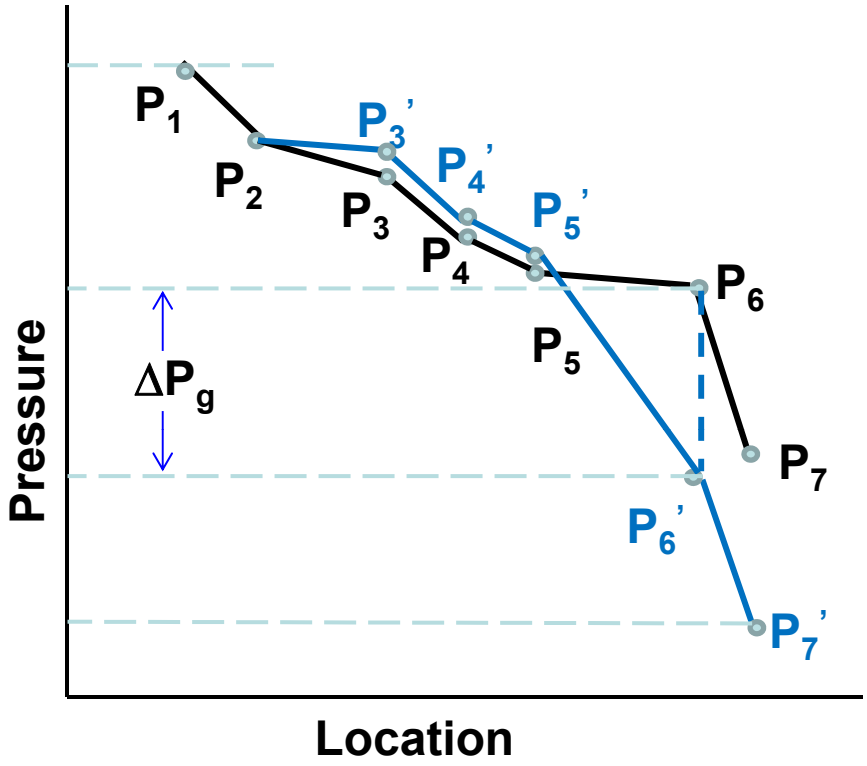
$$\Delta P_{tot} = \Delta P_{groove} + \Delta P_{vl} + \Delta P_{cond} + \Delta P_{ll} + \Delta P_{wick} - \Delta P_g$$

$$\Delta P_g = (\rho_l - \rho_v) g \Delta H$$

ΔH is the height of the condenser above the evaporator in the gravity field.

Pressure profile in Anti-Gravity LHP Operation Capillary Force Driven





- For a horizontal condenser:

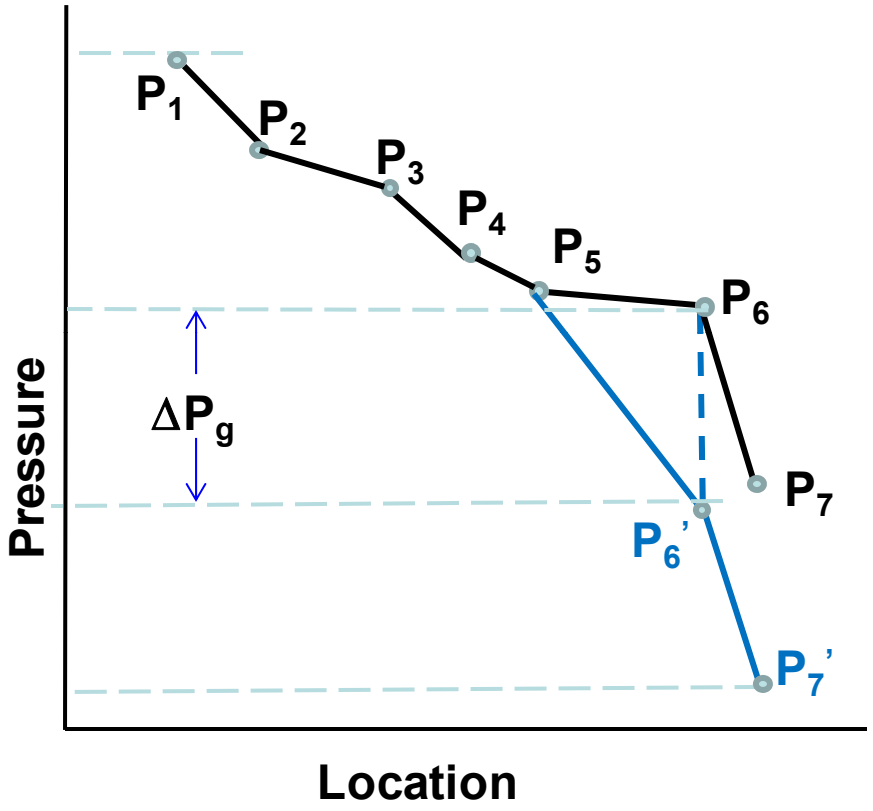
$$P_3' - P_3 = -\rho_v g \Delta H$$
$$P_4' - P_4 = P_5' - P_5 = -\rho_v g \Delta H$$
$$P_5' - P_6' = -\rho_l g \Delta H$$

- ΔP_g is the net pressure head to be added to total pressure drop.

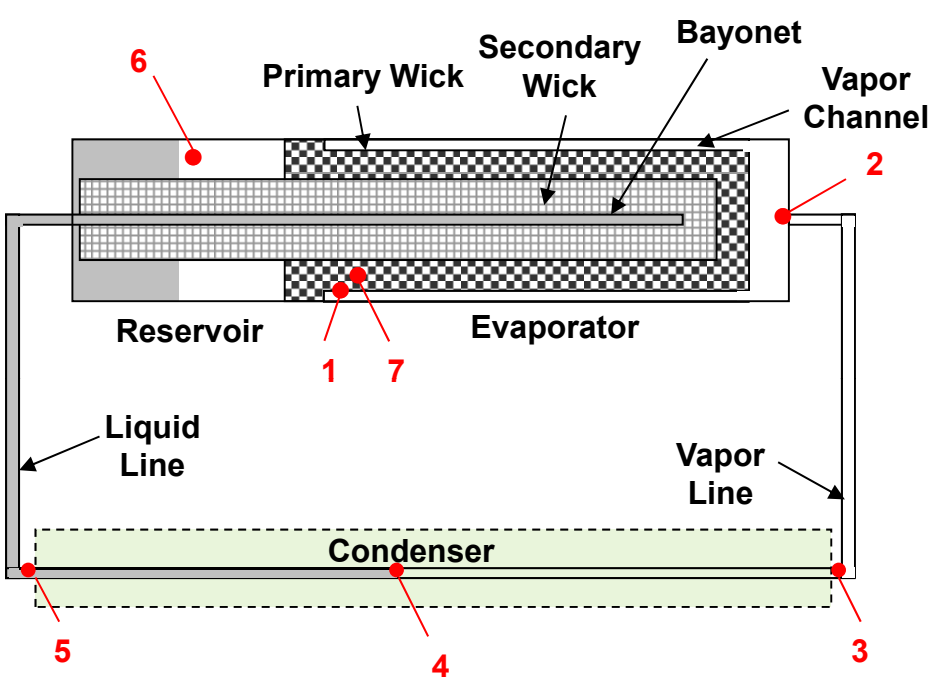
$$\Delta P_g = P_6 - P_6' = -(\rho_l - \rho_v) g \Delta H$$

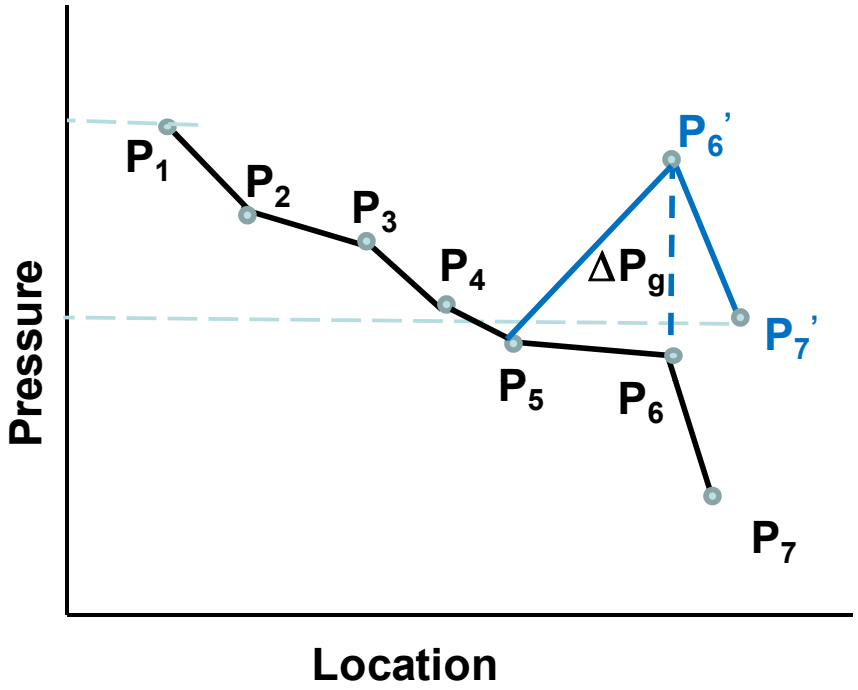
Simplified Pressure Profile in Anti-Gravity LHP Operation - Capillary Force Driven

- The pressure rise of $-\rho_v g \Delta H$ at P_3, P_4, and P_5 is ignored.
- The pressure goes from P_5 to P_6' directly with an additional gravitational pressure head of $-\Delta P_g$.
- ΔP_g is "felt" at the liquid/vapor interface at the outer surface of the capillary wick.
- Viscous pressure drops remain practically the same.
- Heat transport capability decreases compared to gravity-neutral configuration.
- $P_1 > P_4 > P_6$', and $T_E > T_{cond} > T_{cc}$



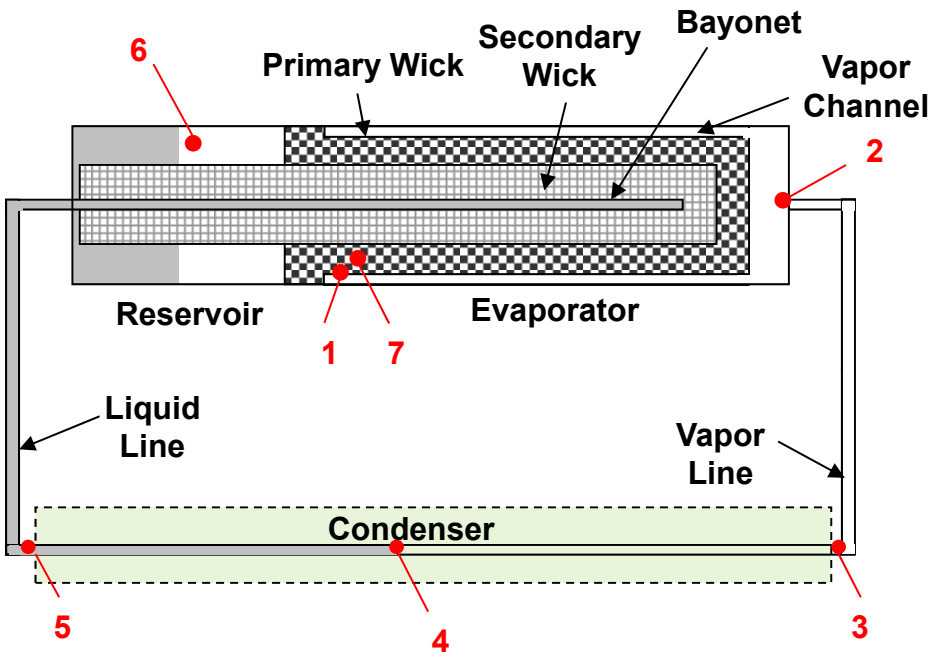
Simplified Pressure Profile in Gravity-Assist LHP Operation - Capillary Force and Gravity Co-Driven

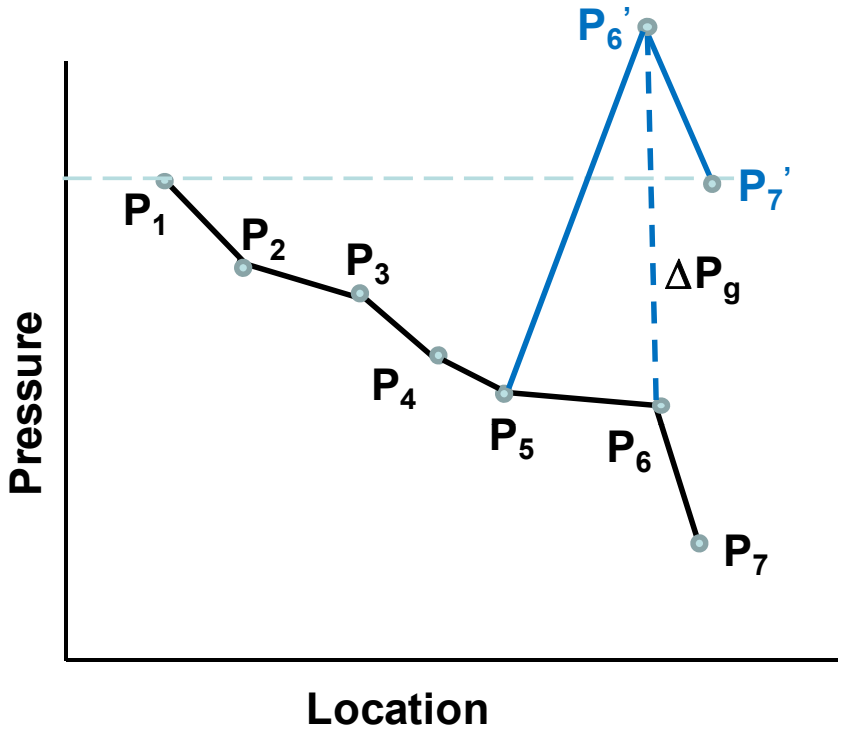




- Heat load > threshold heat load (vapor line contains all vapor).
- Gravity assist raises the reservoir pressure from P_6 to P_6'
- All other pressures are governed by P_6'
- Viscous pressure drops remain practically the same.
- Maximum heat transport capability increases compared to no gravity.

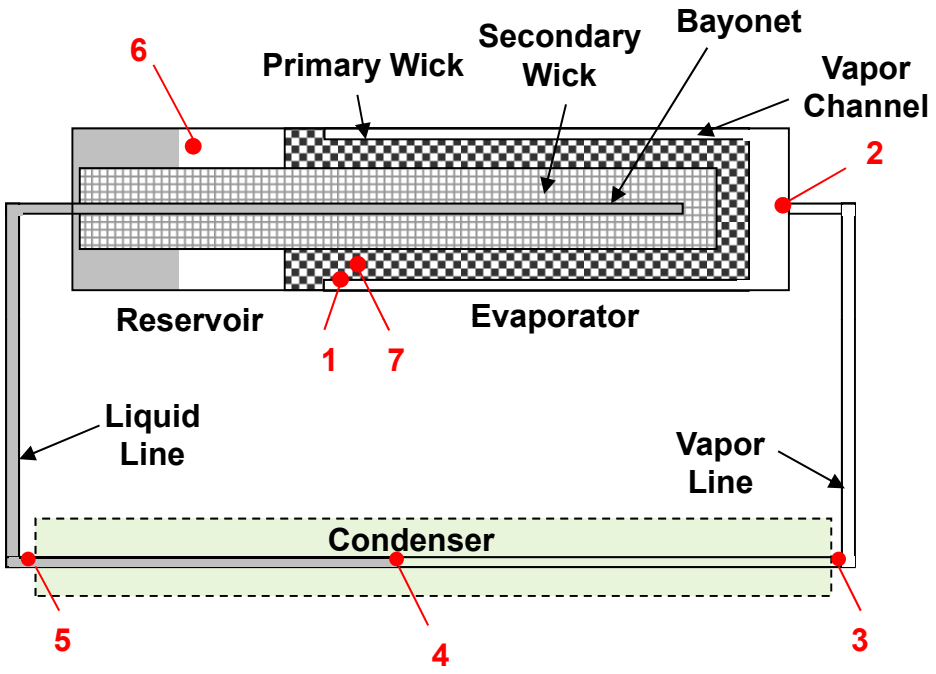
Simplified Pressure Profile in Gravity-Assist LHP Operation - Transition Heat Load

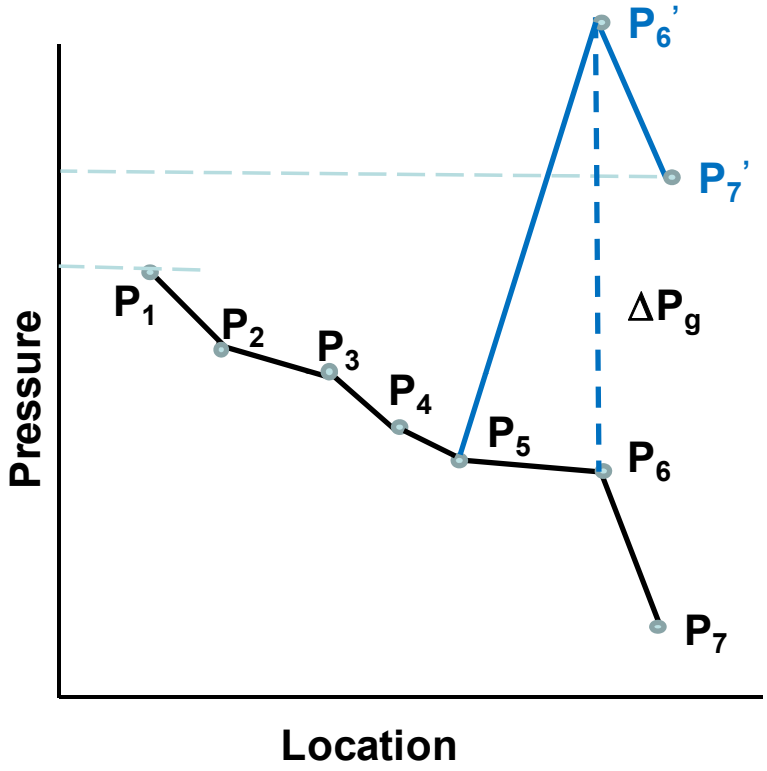




- Heat load = threshold heat load (vapor line has all vapor).
- $P_1 = P_7'$ and $\Delta P_{tot} = \Delta P_{cap} = 0$
- Gravity assist raises the reservoir pressure from P_6 to P_6'
- All other pressures are governed by P_6'
- Maximum heat transport capability increases compared to no gravity.
- The threshold heat load is a function of sink temperature and ΔP_g

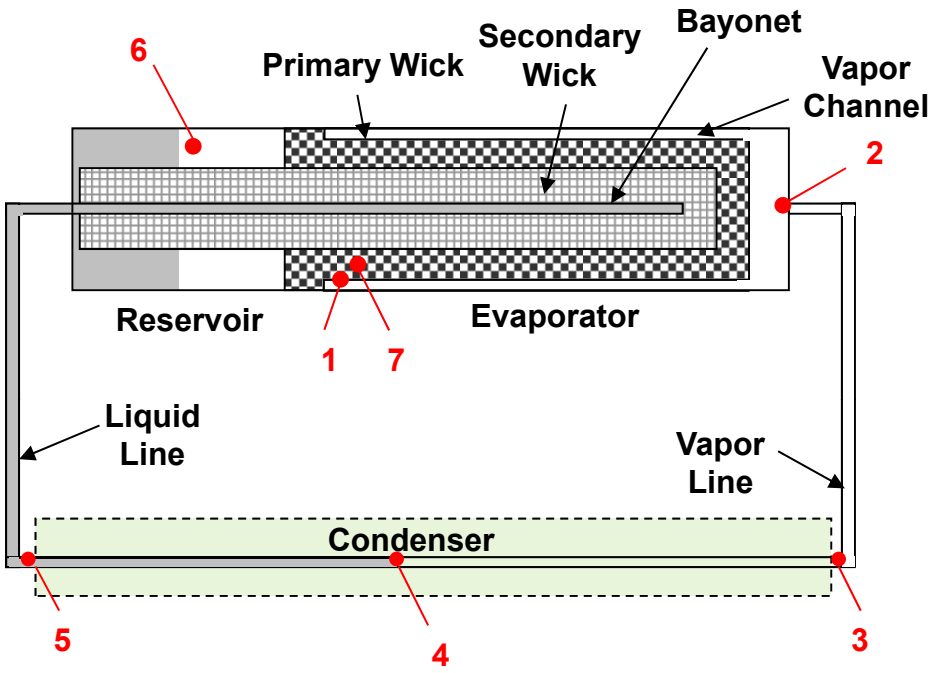
Simplified Pressure Profile in Gravity-Assist LHP Operation - Gravity Driven (1)

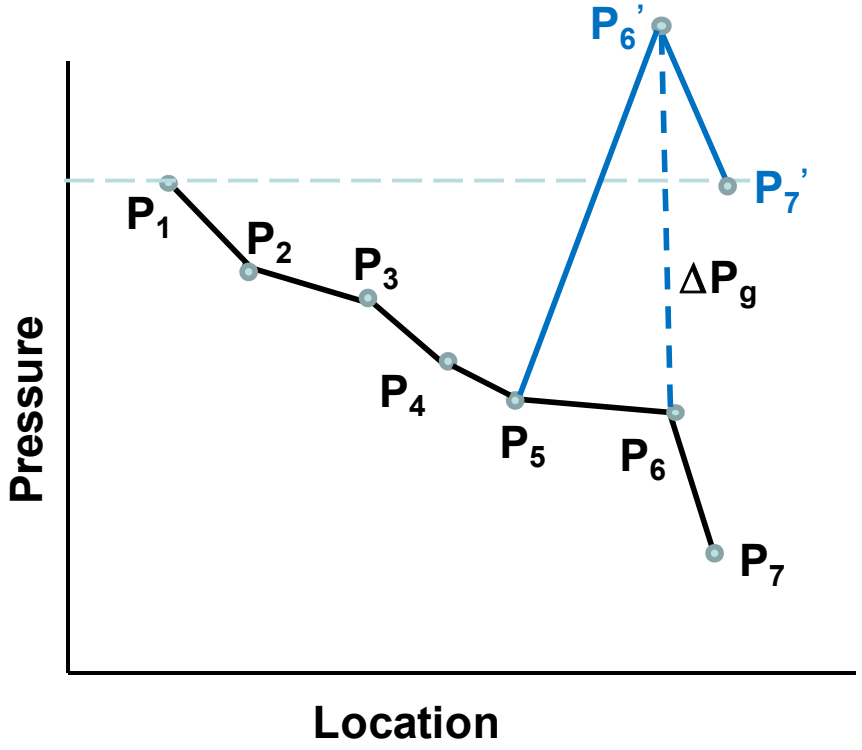




- When $P_7' > P_1$, liquid will be pushed into evaporator vapor grooves.
- Gravity will induce an additional liquid flow so that the viscous pressure drops will increase until $P_7' = P_1$
  - The gravitational pressure head is the key for liquid flow rate.
- Vapor line will contain both liquid and vapor.

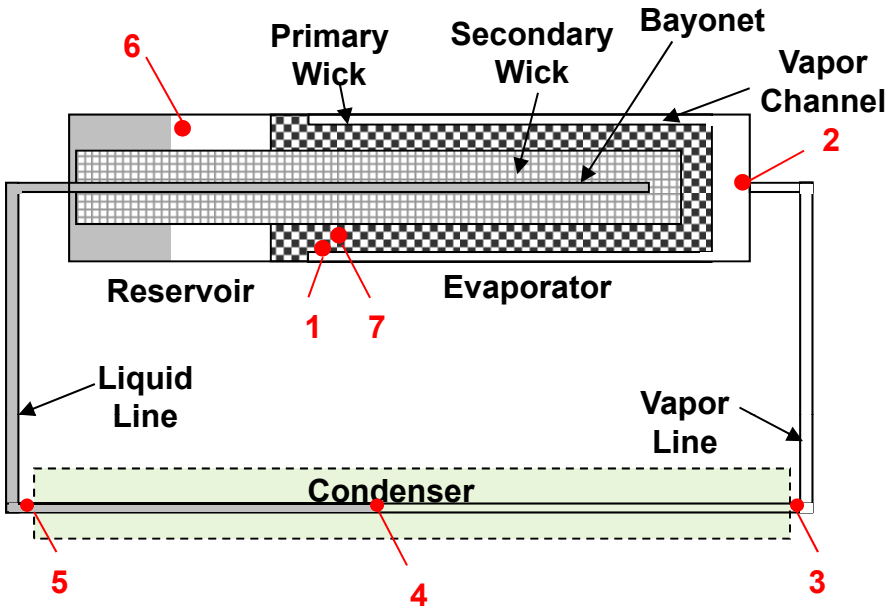
Simplified Pressure Profile in Gravity-Assist LHP Operation - Gravity Driven (2)

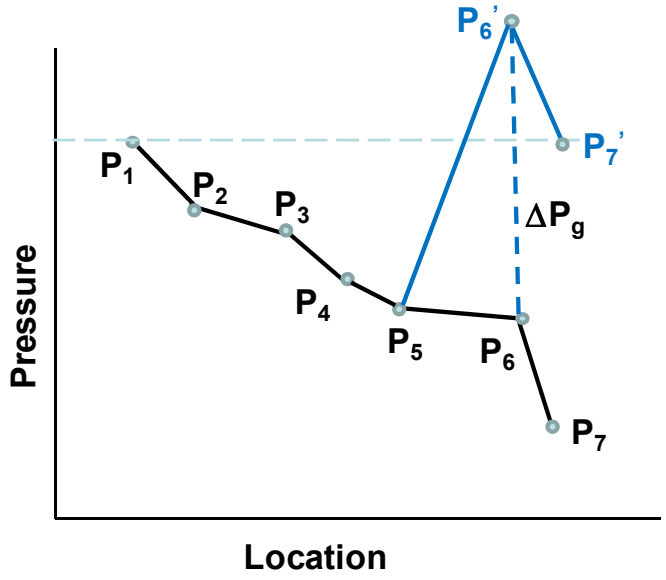




- Heat load < threshold heat load => gravity driven operation
- Gravity will induce an additional liquid flow so that the viscous pressure drops will increase until $P_7' = P_1$
- All pressures are governed by P_6', and the corresponding saturation temperature is a function of heat load, sink temperature, and ΔP_g

Governing Equations for Gravity-Driven LHP Operation (1)





$$\Delta P_g = (\rho_l - \bar{\rho}) g \Delta H$$

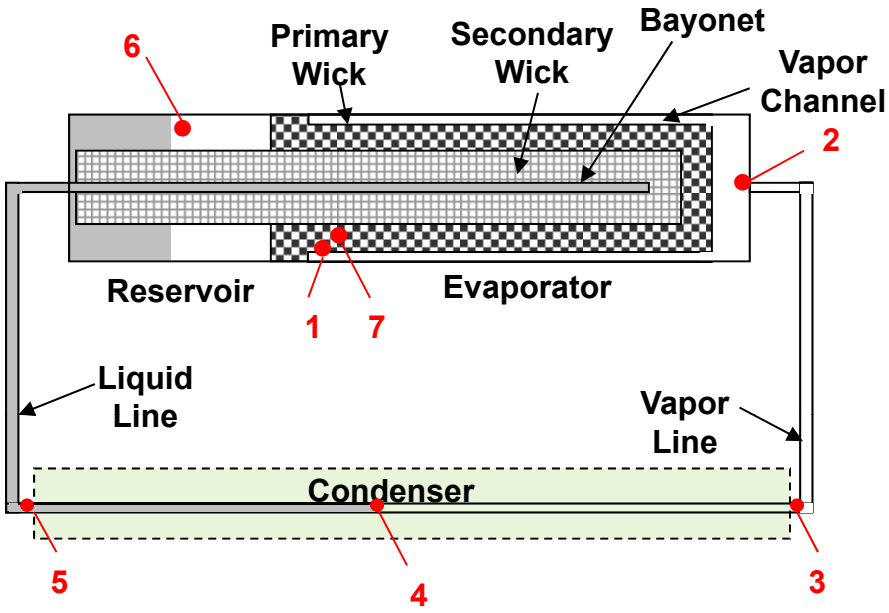
$$\Delta P_g = \Delta P_{groove} + \Delta P_{vl} + \Delta P_{cond} + \Delta P_{ll} + \Delta P_{wick}$$

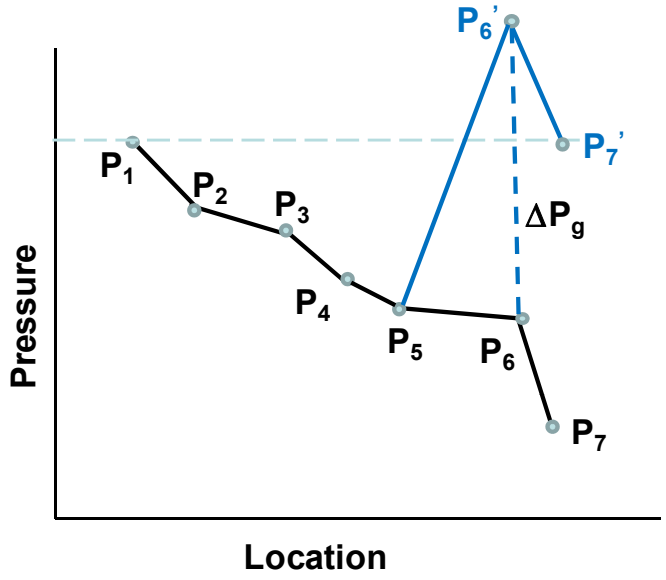
$$(\rho_l - \bar{\rho}) g \Delta H = \Delta P_{groove} + \Delta P_{vl} + \Delta P_{cond} + \Delta P_{ll} + \Delta P_{wick}$$

$$\bar{\rho} = \rho_v \alpha + \rho_l (1 - \alpha)$$

$$\alpha = \frac{x \rho_l}{[x \rho_l + (1 - x) \rho_v S]}$$

Governing Equations for Gravity-Driven LHP Operation (2)





$$\dot{m} = \dot{m}_v + \dot{m}_l$$

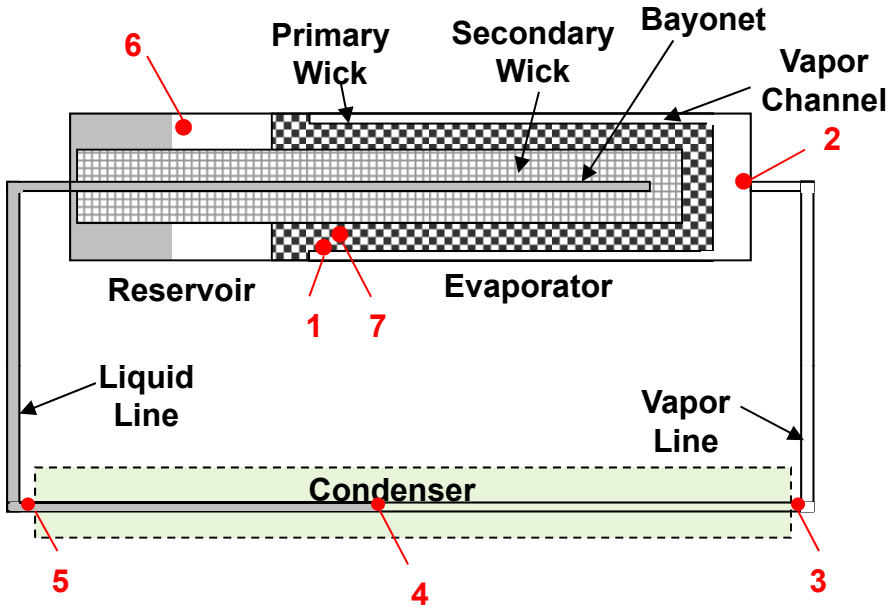
$$Q_{leak} = G_{E,cc}(T_E - T_{cc})$$

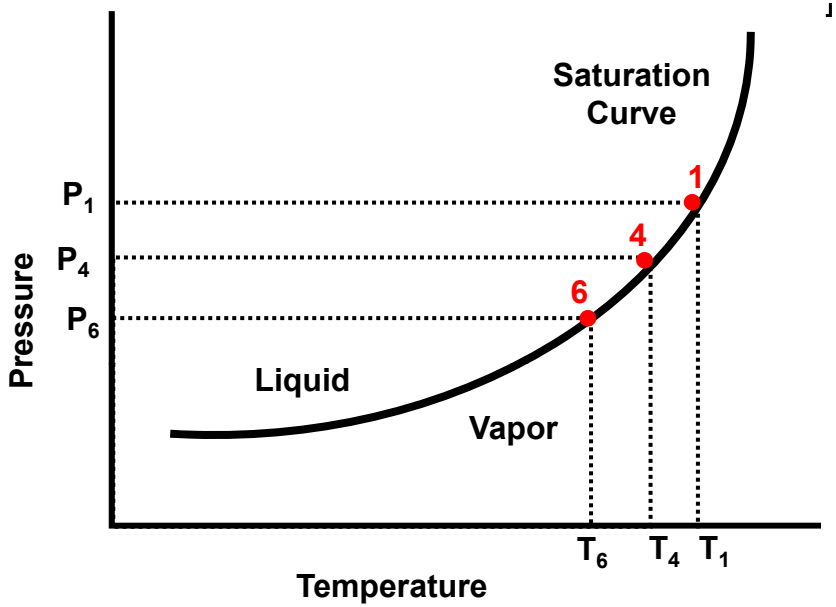
$$Q_{sub} = \dot{m} C_p (T_{cc} - T_{in})$$

$$\dot{m}_v = \frac{Q_E - Q_{leak} - Q_{sub}}{\lambda}$$

$$-\dot{m}\frac{dh}{dL} = \frac{G_{vl,a}}{L_{vl}}(T - T_a)$$

Pressure-Temperature Constraints in LHP Operation





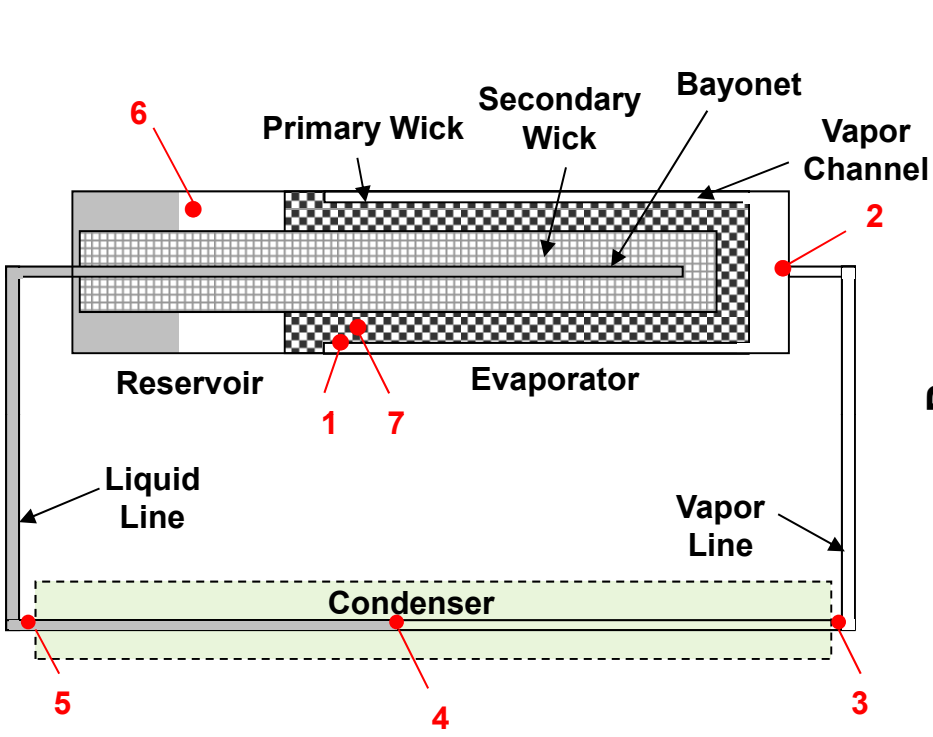
$$P_E - P_{cc} = (dP/dT)\,(T_E - T_{cc})$$

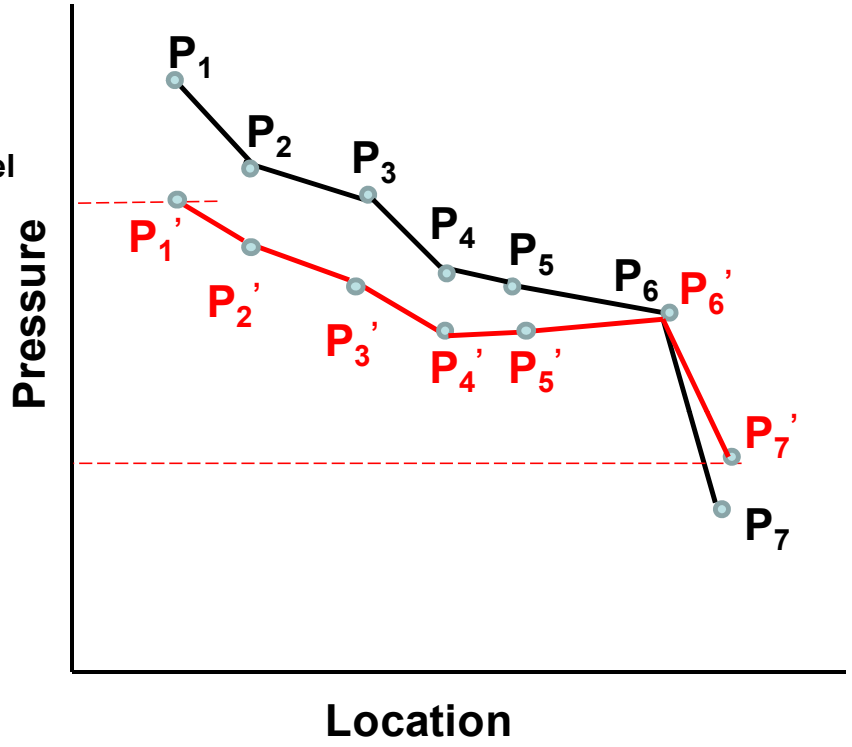
$$P_E - P_{cond} = (dP/dT)\,(T_E - T_{cond})$$

$$P_{cond} - P_{cc} = (dP/dT)\,(T_{cond} - T_{cc})$$

- **These constraints can be used for loop operating temperature control and loop shutdown.**

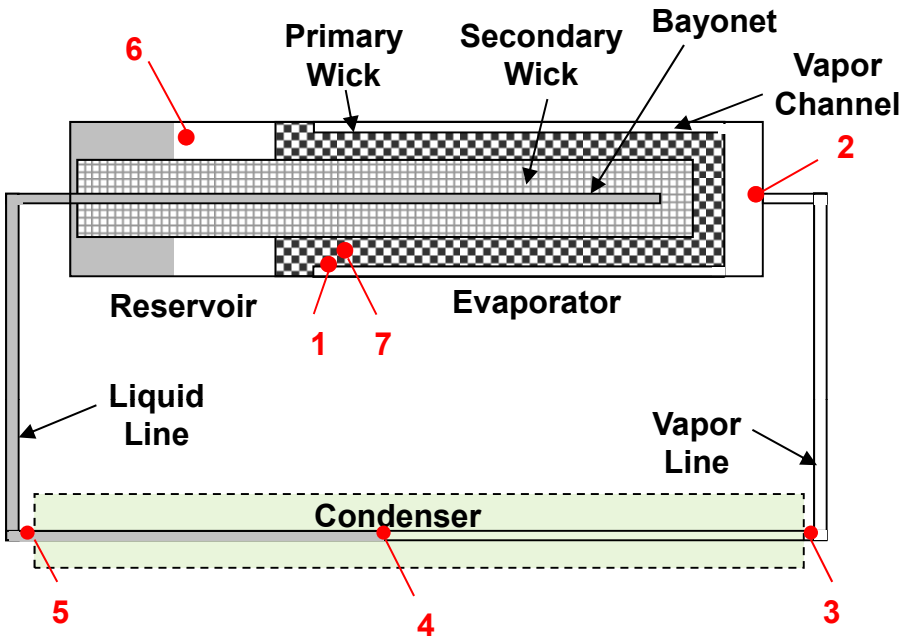
Pressure Profile in LHP Operation
Liquid Reverse Flow/Gravity Neutral

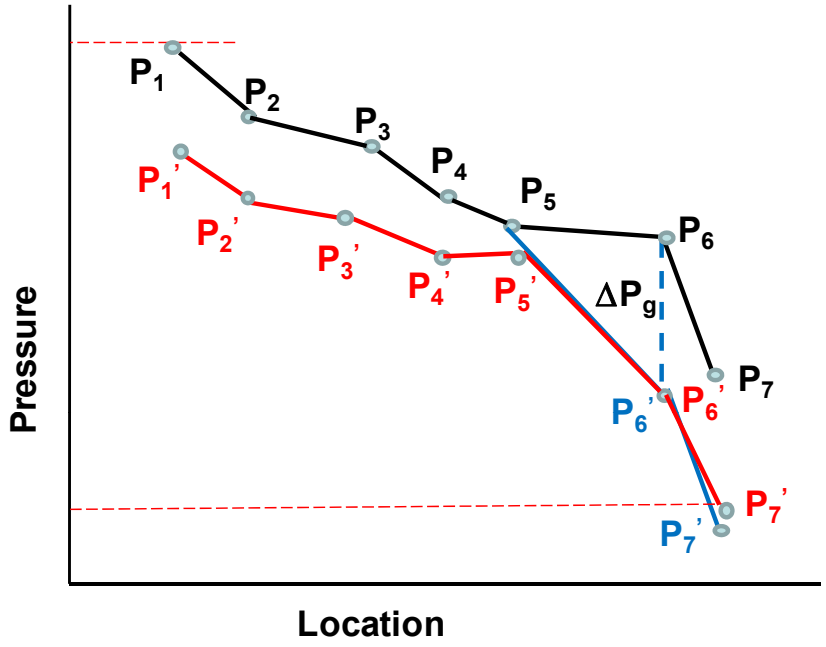




- Absolute pressures with a reverse liquid flow are shown in red.
  - A snapshot (transient phenomenon)
- Reverse flow will begin when P_6' exceeds P_5' and P_4' . The loop will be shut down when P_7' > P_1'.
- Forward vapor flow in vapor line, reverse liquid flow in liquid line
- P_6' - P_5' = viscous pressure drop due to reverse liquid flow.

Pressure Profile in LHP Operation
Liquid Reverse Flow/Anti-gravity



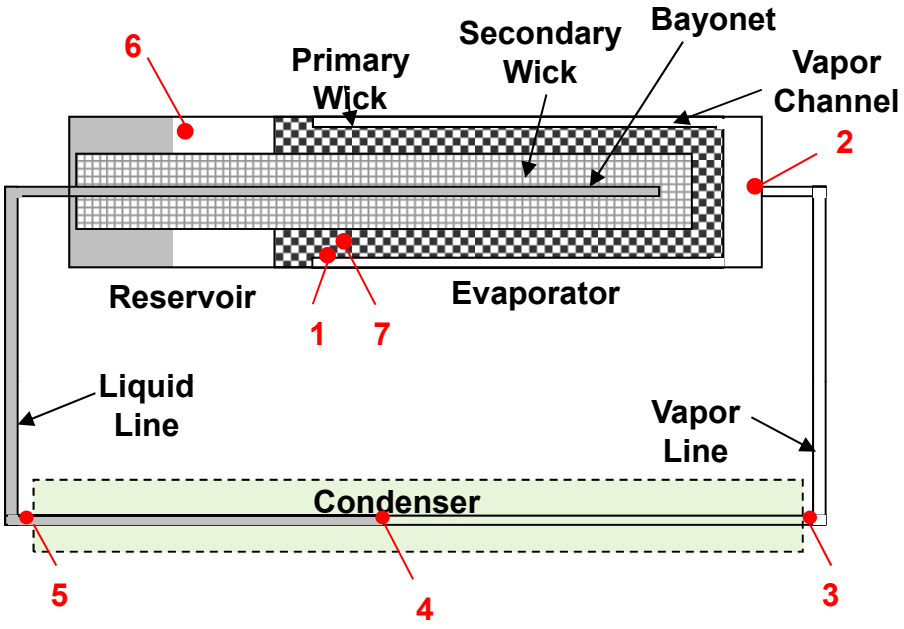


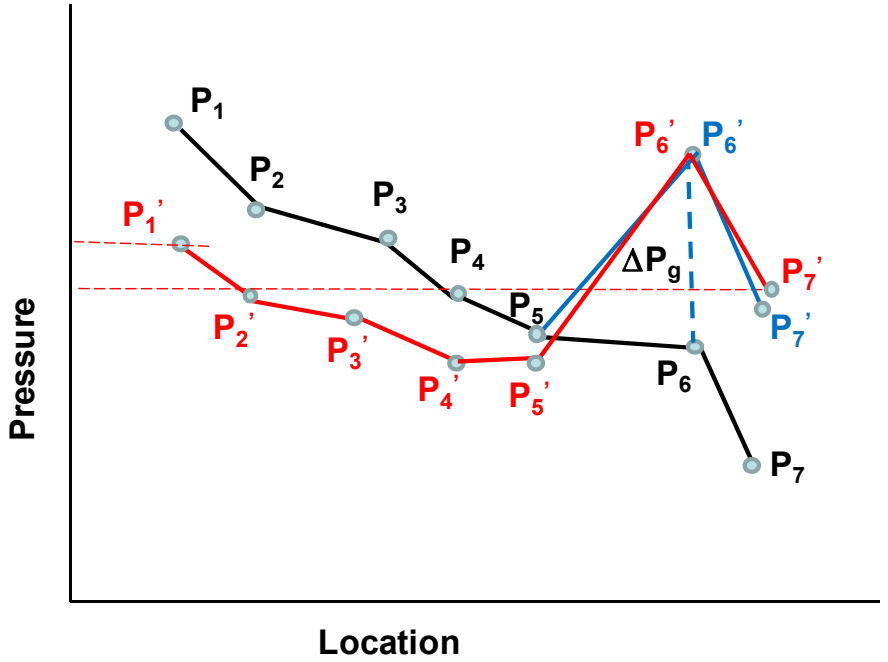
- Absolute pressures with a reverse liquid flow are shown in red.
- When T_6 rises faster than T_1, P_6' also rises faster than P_1' and P_4'
- Reverse flow will begin when the difference between P_4' and P_6' (due to temperature difference in T_4 and T_6) cannot support the liquid column on the liquid line.

$$P_{cond} - P_{cc} = (dP/dT)\,(T_{cond} - T_{cc})$$

- The loop will shut down when $P_7' > P_1'$.

Pressure Profile in LHP Operation
Liquid Reverse Flow/Gravity Assist





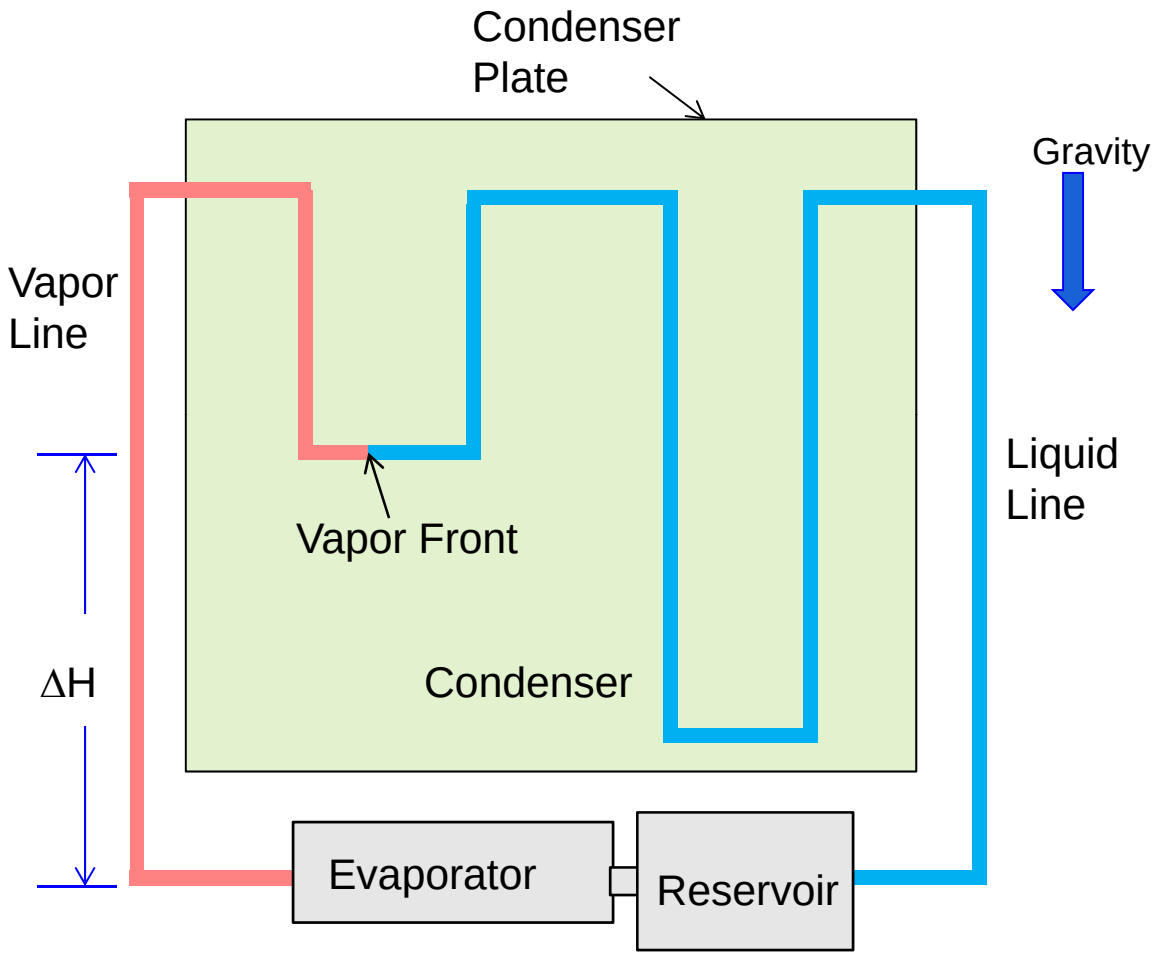
- Absolute pressures with a reverse liquid flow are shown in red.
- When T_6 rises faster than T_1, P_6' also rises faster than P_1' and P_4'
- Reverse flow will begin when the difference between P_6' and P_4' (due to temperature difference in T_6 and T_4) exceeds what is needed to support the liquid column on the liquid line.

$$P_{cc} - P_{cond} = (dP/dT)\,(T_{cc} - T_{cond})$$

- The loop will shut down when $P_7' > P_1'$.

Gravitational Pressure Head with a Vertical Condenser

$$\Delta P_g = (\rho_l - \rho_v) g \, \Delta H$$



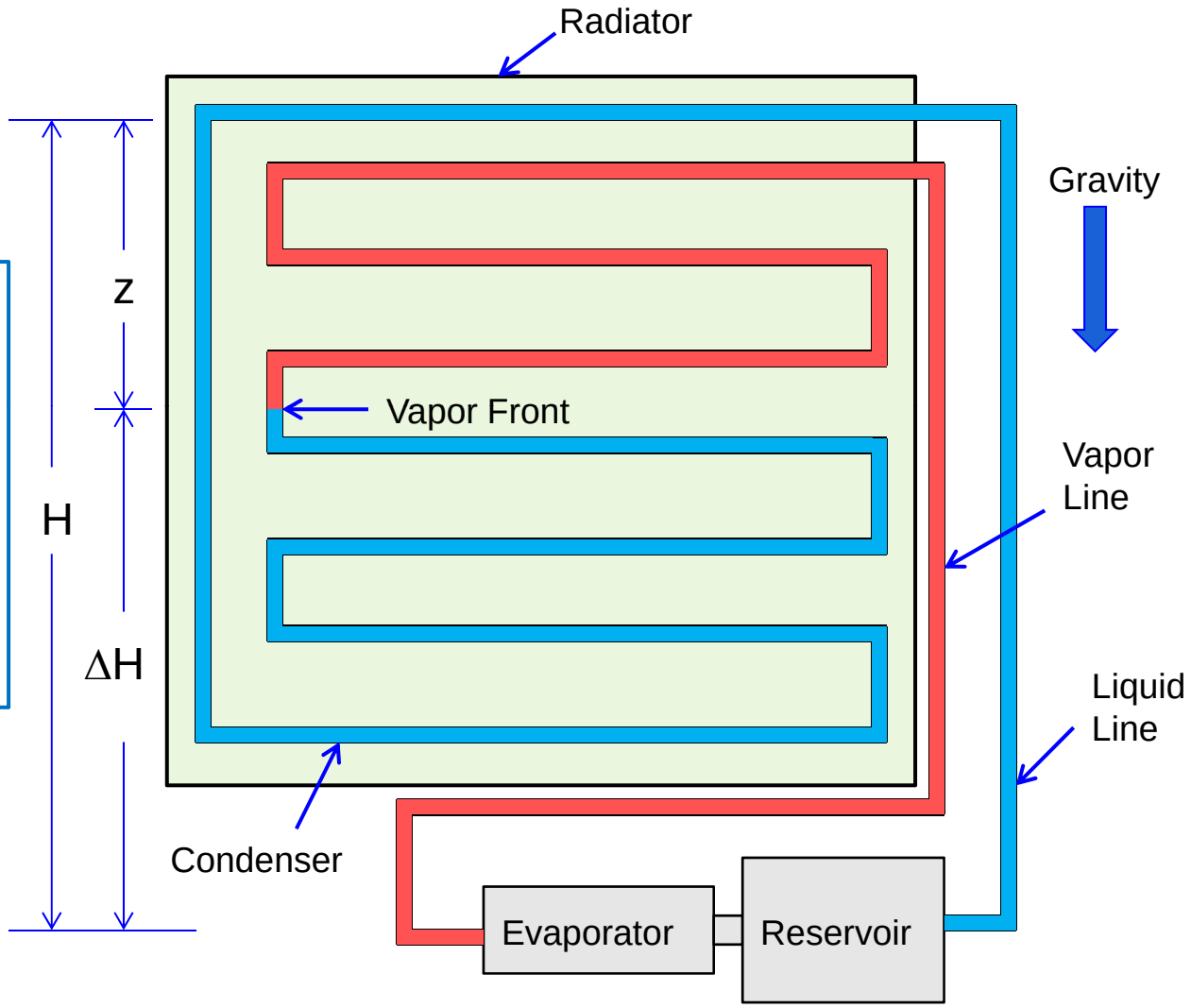
ΔP_g varies with the location of the vapor front in condenser.

Gravitational Pressure Head with a Vertical Condenser

$\Delta P_g = (\rho_l - \rho_v) g \, \Delta H$

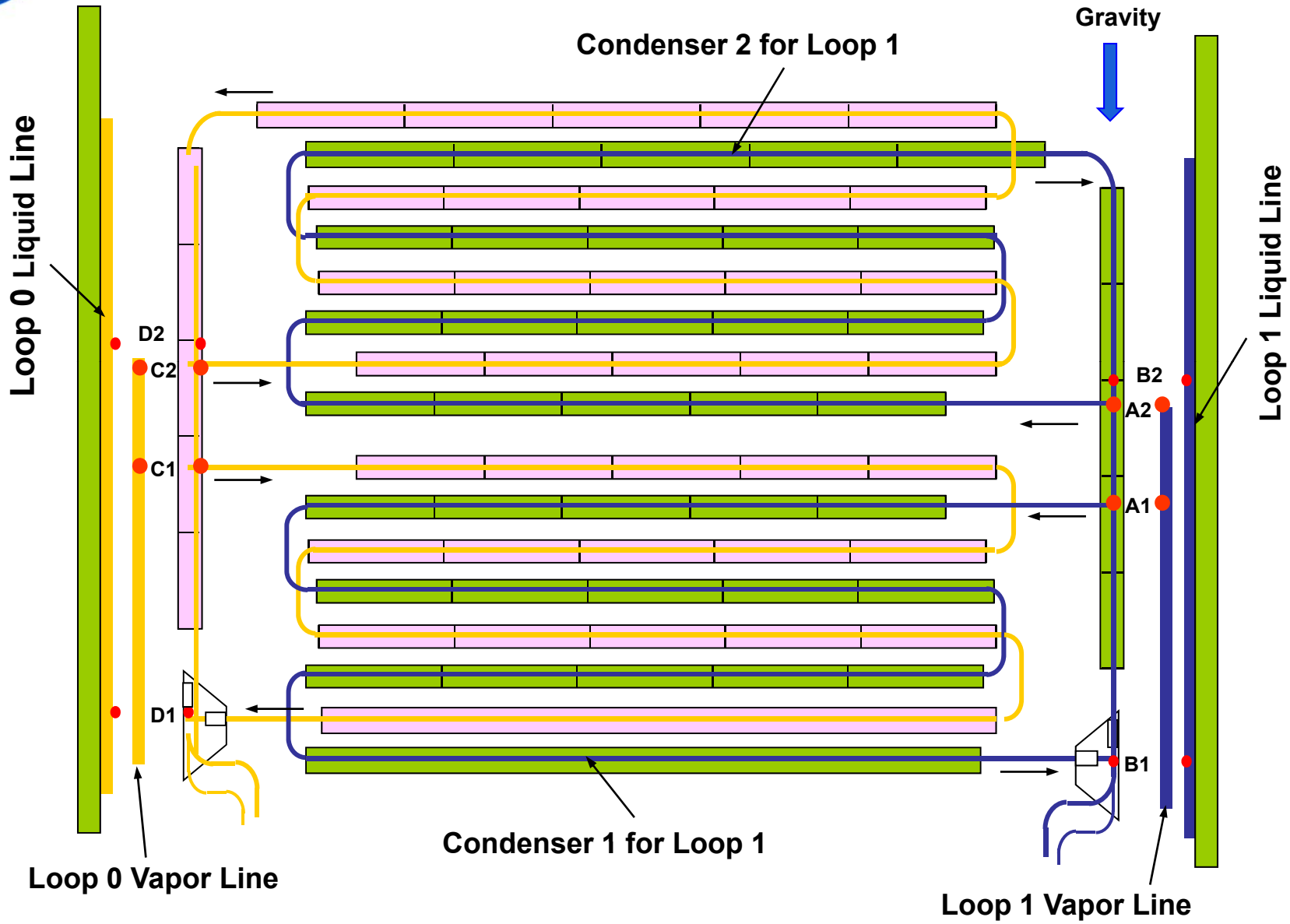
$\Delta H = H - z$

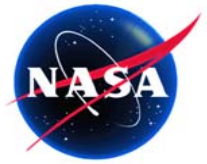
ΔH and ΔP_g vary with the vapor front position.



ΔP_g varies with the location of the vapor front in condenser.

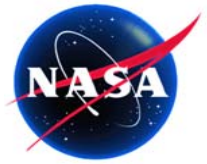
Swift BAT Instrument LHP Condenser Layout

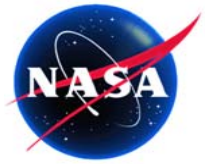




Summary and Conclusions (1)

- Gravity can have profound effects on LHP operation.
- Under gravity neutral and anti-gravity configurations, the flow circulation in an LHP is solely driven by the capillary force.
  - An additional ΔP_g in anti-gravity configuration working against the capillary force
- For a given ΔH, there exist a transitional heat load where the total viscous pressure drop is balanced by the gravitational pressure head.
  - The flow in the LHP is capillary force and gravity co-driven when the heat load is above the transitional heat load.
  - The flow in the LHP is gravity driven when the head load is below the transitional heat load.
- In gravity-driven LHP operation, the capillary force is inactive. Gravity will induce an additional liquid mass flow rate. The fluid is in two-phase status for flow in vapor grooves, vapor line, and condenser. Liquid will flow along the liquid line and capillary wick. There is no pure vapor flow.



Summary and Conclusions (2)

- The transition heat load can be found analytically by solving governing equations based on mass, momentum, and energy balance.
  - The operating temperature and transitional heat load must be found simultaneously iteratively.
- Under gravity-driven mode, the additional liquid mass flow rate, vapor quality at evaporator exit, and loop operating temperature can be found analytically by solving governing equations based on mass, momentum, and energy balance.
  - Again, an iterative procedure is needed.
- When the reservoir temperature rises faster than the evaporator temperature, a reverse liquid flow could occur in the liquid line, which co-exists with the forward vapor flow in the vapor line.
- A condenser with multiple parallel and vertical segments can be very difficult to model analytically under the gravity-assist configuration.